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Influence of Angular Orientation of the Embedded Highly Birefringent Fiber on PMD Changes under Axial Stress

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In the paper we present results of the research on polarization mode dispersion changes inside the polarimetric optical fiber sensors based on highly birefringent optical fibers embedded into composite materials with different angular orientations of the optical axes. Based on measurements made for different types of highly birefringent optical fiber sensors we have shown that strain sensitivities after lamination process are different in comparison to the data obtained before lamination. Our results indicate that polarization mode dispersion in side-hole highly birefringent fibers under axial stress strongly depends on fiber orientation in the composite material suggesting that orientation of the polarization axes of the highly birefringent fiber can be responsible for behavior of the fiber inside the composite material.

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1. Introduction

Recently, many experiments and research have been carried out on laminated composite materials. The key issue in structures design is to obtain optimal mechanical properties and also possibility of their monitoring [1–3]. Such a control can be achieved by embedding highly birefringent (HB) optical fiber sensors inside a composite material during the lamination process. However, influence of the lamination process on strain sensitivity of the HB fibers embedded in the composite material remains still underexplored.

In our research we are dealing with polarization mode dispersion (PMD) inside different types of HB fiber sensors embedded into a composite material. In HB optical fibers in a single-mode regime there is no mode coupling and as a result PMD value is equal to differential group delay (DGD) assuming that chromatic dispersion is negligible. The phase difference $\Delta\delta$ and modal birefringence $\Delta\beta$ can be defined as:

$$\Delta\delta = L(\Delta\beta)\,,$$

$$\Delta\beta = k\Delta n_{\text{eff}}\,,$$

where L is fiber length, $\Delta\beta$ is difference between propagation constants, k is the wave vector, and n_{eff} is the difference between refractive indices of the both orthogonal components of fundamental mode.

Under the influence of longitudinal strain internal linear birefringence of the HB fiber changes according to the following formula [8]:

$$\Delta\beta(\varepsilon) = \Delta\beta^0 + \operatorname{sgn}\left(\frac{\mathrm{d}(\Delta\beta)}{\mathrm{d}\varepsilon}\right)\varepsilon\frac{2\pi}{T_\varepsilon L}\,, \quad (1)$$

where T_ε is an experimentally measurable parameter corresponding to the amount of strain needed to induce a 2π phase shift of the polarized light detected at the output, and L is the length of the optical fiber under longitudinal strain.

For the HB fibers in which birefringence is caused by stress applying parts introduced in cladding close to the region of the fiber (i.e. bow-tie fiber) $\Delta\beta$ is nearly wavelength independent and chromatic dispersion of the modal birefringence is negligible. For any other types of the HB fibers (i.e. photonic crystal fibers) $\Delta\beta_L$ strongly depends on the wavelength and chromatic dispersion component should be added to the expression on the polarization mode dispersion. On the other hand, chromatic dispersion is longitudinal strain independent and PMD depends only on changes in birefringence. The PMD dependence on the longitudinal strain can be described according to the following equation [4]:

$$\frac{\Delta\tau}{L} \cong \frac{1}{ck}\left(\Delta\beta_L + k\omega\frac{\mathrm{d}(\Delta n_{\text{eff}})}{\mathrm{d}\omega} + \operatorname{sgn}\left(\frac{\mathrm{d}(\Delta\beta_L)}{\mathrm{d}\varepsilon}\right)\varepsilon\frac{2\pi}{T_\varepsilon L}\right), \quad (2)$$

where c is the light velocity in the vacuum, $\omega = 2\pi c/\lambda$ is the angular frequency of light. This explains that PMD

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depends on the phase birefringence as well as on chromatic dispersion. From the formula (5) it is evident that changes in linear birefringence influence DGD in the HB fibers. In consequence, DGD increases linearly with longitudinal strain.

2. Smart structures

One of the potential applications of the HB polarimetric sensors may be monitoring of the elements made of composite materials that are exposed to the influence of vibrations, temperature, pressure and other factors. Composite materials are new structures made of stiff glass or carbon fibers that provide mechanical properties and are placed in matrices based on epoxy or polyester resins that bond composite layers. From many kinds of composite materials, we have focused on composites based on laminates which are commonly used in avionic industry. The main advantage of composite materials is their tensile strength that is much higher than for steel, and their lower weight in comparison with steel. Additionally, they possess high durability caused by high resistivity on external factors and low cost of their maintenance.

Introducing of the HB optical fibers into composite material structure is a novel approach to sensing techniques that overcomes limitations of typical sensors used nowadays. It gives possibility to continuously monitoring the structural health over the lifecycle of the component made of the composite material, and also minimizes the life cycle costs. Nowadays, typical inspection procedures in the aircraft industry represent 25% of the total life cycle costs. Implementing of the HB optical fiber polarimetric sensors into composite structures will additionally minimize these costs. Similar approach has been presented in [5] where authors implemented a fiber Bragg grating (FBG) into composite material to monitor the structure of the sample. In such a solution the FBG measures the absolute value of strain and temperature in one point. Unlike the measurements with FBG, polarimetric fiber sensors embedded in composites are only sensitive to strain and show the mean value.

To check the feasibility of embedding HB polarimetric optical fiber sensors into composite material structure, a few samples have been manufactured with different axial orientations of optical fibers.

3. Experimental setup

The experimental setup has been presented in Fig. 1. The phase change versus strain sensitivity of the polarimetric sensors is measured with a PAT9000B polarimeter. A tunable laser source with a wavelength of 1550 nm is used as an input source.

The fabricated composite material sample was 250 mm long, 35 mm wide and 2.5 mm thick (Fig. 2). We have embedded a set of different types of HB optical fibers, where we can distinguish PANDA, bow-tie, side-hole type

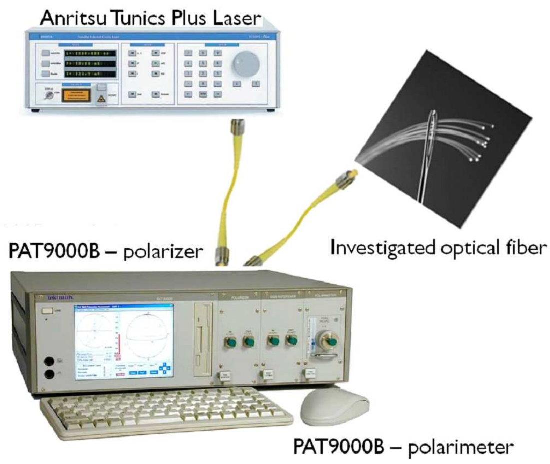

Fig. 1. Experimental setup.

and PCF fibers. In our experiment we have focused on HB optical fibers embedded in the composite material under different axial orientations.

Fig. 2. Composite material sample with set of HB optical fibers embedded inside.

The side-hole fibers are embedded in the same layer of the composite material (Fig. 3). The strain change for this fiber lead to a phase difference between both polarizations of the fundamental mode.

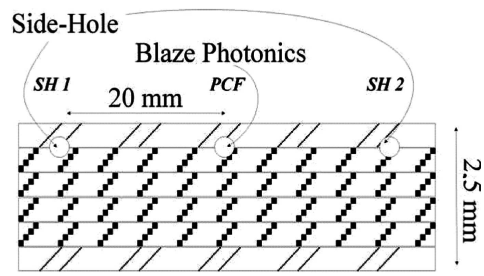

Fig. 3. Schematic cross-section of the composite sample with optical fibers embedded inside.

Measurements made for the side-hole HB fiber sensors show that strain sensitivities are different in HB sensors after the lamination process in comparison to the original values. In our previous results [5–7] made for the composite, the strain sensitivity of the PM-PCF in free space was much lower than that of the side-hole fiber. The strain sensitivity of the PM-PCF fiber was 1.7 rad/(m mstrain) and for side-hole fiber was 4 rad/(m mstrain). After lamination process the strain sensitivities of both types of the optical fibers had similar values. It means that the axial orientation of the HB optical fiber may be responsible for sensing behavior after lamination process.

4. Results

In our present research we have investigated strain sensitivities for side-hole fibers embedded in the composite material with different axial orientations.

The lamination process influenced strain sensitivities of the side-hole fibers under investigation (Fig. 4).

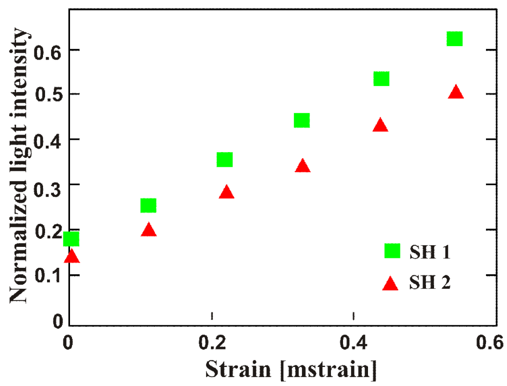

Fig. 4. Comparison of strain sensitivity for two side--hole fibers with different axial orientations inside the composite sample.

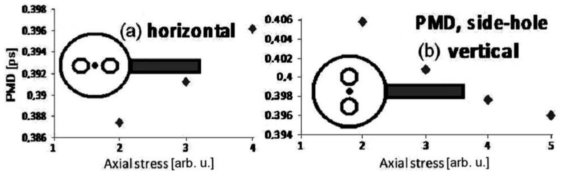

Fig. 5. PMD changes under external axial stress in two HB side-hole fibers oriented horizontally (a) and vertically (b) in the composite sample.

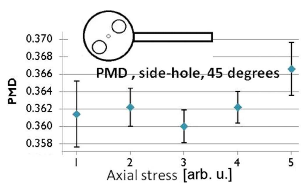

Fig. 6. PMD changes under external axial stress in the side-hole fibers oriented under 45 degrees in the composite sample.

Our approach was to estimate the influence of optical fiber axis orientation on sensors sensitivities. We have measured the PMD of different optical fibers embedded in the composite sample in function of transverse stress according to the following formula (1).

In case of side-hole fibers, for horizontal axial orientation we have observed that relative PMD value were increasing with induced axial force (Fig. 5a), unlike to vertical axial orientation where relative PMD values were decreasing with induced axial stress.

The measurements were repeated also for axial orientation under 45 degrees. In this case the relative PMD value did not change significantly (Fig. 6).

This suggests that the orientation of the polarization axis of the HB fiber can be responsible for behavior of the fiber inside the composite material.

Additionally, we have compared the strain sensitivities of HB PCF, bow-tie and side-hole optical fiber sensors. The results are presented in Fig. 7.

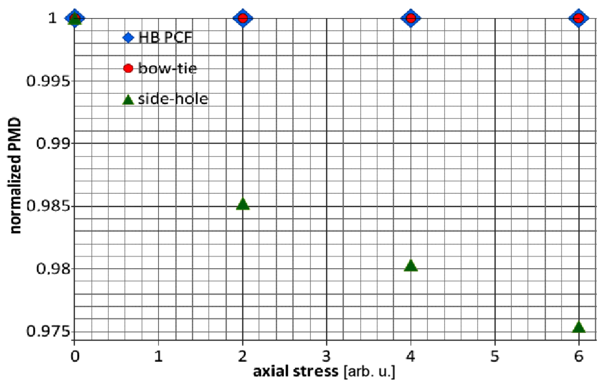

Fig. 7. Comparison of birefringence change in side--hole, bow-tie and HB PCF fibres in composite material under axial stress.

Contrary to the HB PCF and bow-tie optical fibers that are not sensitive to axial stress, the side-hole fiber with the birefringence axis orientation presented in Fig. 5b is axial stress sensitive.

Such a behavior may depend on type of coating layer used in the optical fiber. Depending on the stiffness of the coating the fiber optic sensor may be more sensitive.

5. Conclusions

Measurement results presented in the paper show that PMD changes depend on axis angular orientation of the HB optical fibers that are embedded in the composite material influenced by external axial stress. We have noticed that lamination process has a significant influence on HB fiber sensitivity induced by the axial stress. Also the coating of the optical fiber may have influence on sensitivity of the sensor. As it was shown in Fig. 4 strain sensitivities for the two side-hole fibers changed dramatically after lamination process.

Further research on influence of coating on strain sensitivity is still in progress.

Acknowledgments

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